

USING NUMERICAL MODELING TO SIMULATE SPACE CAPSULE GROUND LANDINGS

Ernie Heymsfield Ph.D., P.E.

Associate Professor
University of Arkansas
Department of Civil Engineering
4190 Bell Engineering Center
Fayetteville, AR 72701
Phone: (479) 575-7586
Fax: (479) 575-7186
E-mail: ernie@uark.edu

Edwin L. Fasanella Ph.D.

Aerospace Research Engineer
Structural Dynamics Branch
NASA Langley Research Center
Hampton, VA 23681
Phone: (757) 864-4345
Fax: (757) 864-8547
E-mail: Edwin.L.Fasanella@nasa.gov

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USING NUMERICAL MODELING TO SIMULATE CAPSULE MODULE GROUND LANDINGS

ABSTRACT

Experimental work is being conducted at the National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC) to investigate ground landing capabilities of the Orion crew exploration vehicle (CEV). The Orion capsule is NASA's replacement for the Space Shuttle. The Orion capsule will service the International Space Station and be used for future space missions to the Moon and to Mars. To evaluate the feasibility of Orion ground landings, a series of capsule impact tests are being performed at the NASA Langley Landing and Impact Research Facility (LandIR). The experimental results derived at LandIR provide means to validate and calibrate nonlinear dynamic finite element models, which are also being developed during this study. Because of the high cost and time involvement intrinsic to full-scale testing, numerical simulations are favored over experimental work. Subsequent to a numerical model validated by actual test responses, impact simulations will be conducted to study multiple impact scenarios not practical to test. Twenty-one swing tests using the LandIR gantry were conducted during the June 07 through October 07 time period to evaluate the Orion's impact response. Results for two capsule initial pitch angles, 0° and -15°, along with their computer simulations using LS-DYNA are presented in this article. A soil-vehicle friction coefficient of 0.45 was determined by comparing the test stopping distance with computer simulations. In addition, soil modeling accuracy is presented by comparing vertical penetrometer impact tests with computer simulations for the soil model used during the swing tests.

INTRODUCTION

The NASA Langley Research Center (LaRC) gantry at the Landing and Impact Research (LandIR) facility is a steel A-frame structure 240 ft. (73.1 m) high by 400 ft. (121.9 m) long with a 265 ft. (80.8 m) base. The LaRC gantry has the largest lift capability among all full-scale impact testing facilities worldwide at 64,000 lb. (284.7 kN). The LandIR was originally constructed as the Lunar Landing Research Facility in 1965 for the purpose of training Apollo astronauts for lunar landings. In 1972, the facility was modified to perform crashworthiness research of full-scale civil aviation aircraft and helicopters. The facility was one of the first capable of conducting full-scale aircraft crash tests such that a vehicle impacts a surface with both horizontal and vertical velocity components. During a swing test, the swing and pull-back cables are adjusted to position the test vehicle, FIGURE 1. Immediately prior to impact, the swing cables are pyrotechnically disengaged from the test vehicle to create free flight conditions. By adjusting the horizontal position of the gantry bridge and the test vehicle initial height, researchers can adjust the horizontal and vertical components of the aircraft impact velocity by varying the initial test vehicle height. Transducers positioned throughout the test vehicle, on vehicle seats, and dummies typically measure loads, strains, and acceleration time histories. The signals are recorded using multiple 32-channel shock-resistant onboard digital data acquisition (DAS) systems with sample rates from 10,000 to 50,000 per second depending on test requirements.

Over forty general aviation full-scale crash tests have been conducted at LandIR. An article by Jackson and Fasanella summarizes the LandIR test program (Jackson & Fasanella, 2004). Crash testing details for a general aviation aircraft's crashworthiness are included in an article by Jones and Carden (Jones and Carden 1995). Only a limited number of facilities exist worldwide capable of evaluating a full-scale aircraft's crashworthiness. Large vertical drop test facilities capable of full-scale aircraft testing exist at the FAA William J. Hughes Technical Center at Atlantic City, NJ and at Centre d'Essais Aeronautique de Toulouse in France. In 2002, the Italian Laboratory for Impact Tests on Aerospace Structures (LISA) opened to provide aircraft impact testing for water and land impact. Although newer, the LISA facility is 50% the height of the LandIR gantry with 69% of the LandIR gantry's lift capability.

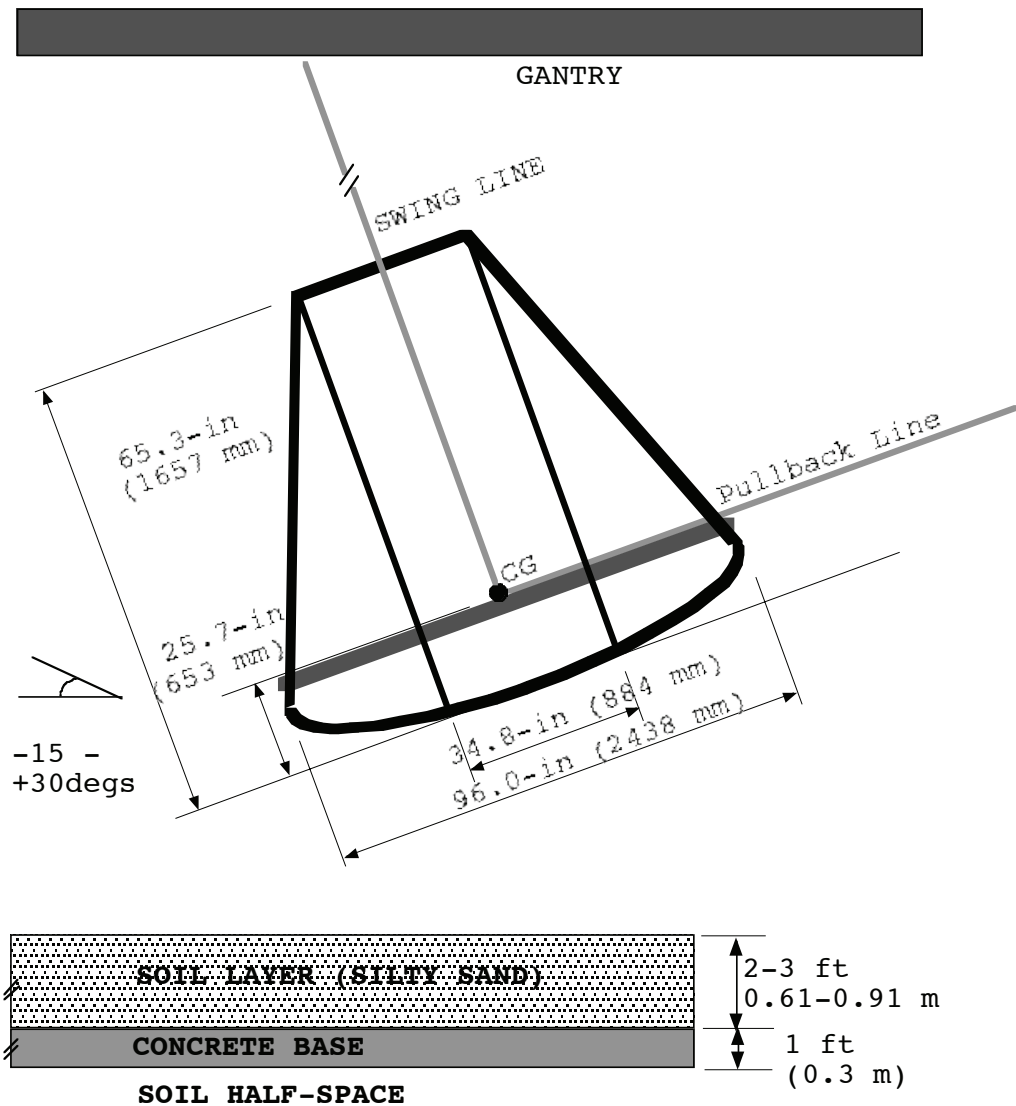


FIGURE 1 Boilerplate Capsule used in Swing Tests

Numerical analysis provides a cost and time effective approach to analyze aircraft crashworthiness by reducing the number of experimental tests required to optimize a vehicle's design. Aircraft crash testing is much more complex and expensive than automotive crash testing and is therefore very limited. The validity of using a numerical analysis is shown in work conducted at NASA LaRC for a vertical drop test of a ATR42-300 commuter-class aircraft (Jackson & Fasanella, 2005). The computer simulations were developed using the commercial code, LS-DYNA, an explicit nonlinear dynamic finite element code typically used for auto crashworthiness (Hallquist, 2006). The numerical results proved to be a good predictor of the actual vertical drop test and

showed the potential of using numerical analysis as a crashworthiness tool. A reference by Fasanella and Jackson outlines a protocol for crash impact data analysis and numerical modeling of a crash test (Fasanella and Jackson, 2002).

Most recently, the LandIR has been utilized in impact studies for the Orion capsule proposed in NASA's Constellation program. Whereas previous full-scale aircraft tests have used the LandIR's concrete impact surface, the Orion capsule is being designed to withstand a ground landing without injuring the crew. Consequently, in studies applicable to Orion, a soil surface has been prepared over the concrete test mat as the impact surface. Aircraft impact tests onto soil introduce added complexities over a hard surface or water impact. In a study conducted by Hashemi and Walton within the European consortium, the importance of soil-aircraft interaction was investigated by comparing A320 Airbus fuselage vertical tests with LS-DYNA numerical simulations (Hashemi and Walton, 2000). In the Hashemi and Walton study, very hard soil, modeled as concrete, is compared with soft sandy-clay soil. Modeling the aircraft fuselage as rigid and as a flexible structure is also considered. Results of the Hashemi and Walton study are given in terms of impact material deformation. More recent work considering soil as an impact surface includes a study conducted at the LandIR on rotorcraft crashworthiness (Fasanella, et al, 2008). Less than 20% of helicopter crashes occur on manmade surfaces; therefore, investigating natural surfaces for crashworthiness is paramount. During the rotorcraft study, experimental vertical drop test results using a 5-ft diameter fuselage and an unpacked sand impact surface were compared with LS-DYNA computer simulations. The helicopter fuselage in the test is comprised of a composite section including a deployable energy absorber system for landing. The Fasanella, et al reference also includes hemispherical penetrometer test results used to characterize soil behavior for the numerical model.

This paper discusses two swing tests of a half-sized boilerplate capsule and their computer simulations. The swing tests were conducted at NASA Langley at 58 ft/s (17.68 m/s) horizontal velocity and with 5 ft/s (1.52 m/s) vertical velocity. The LS-DYNA nonlinear finite element code was used to model the soil and capsule during the swing tests.

SWING TESTS

Twenty-one boilerplate swing tests were conducted over a four-month time period (June 07 – September 07), FIGURE 2. Of these twenty-one tests, ten preliminary vertical drop tests were conducted at the LandIR to exercise the data acquisition system and test setup. An additional, six tests were performed using only the curved base plate, 2,500 lb. (11.12 kN) of the boilerplate shown in FIGURE 1. These swing tests were used to establish a protocol for subsequent swing testing as a function of approach velocity and boilerplate pitch, TABLE 1. Two swing tests, 19 and 20, are presented in this article. The two swing tests are representative of capsule behavior at high horizontal velocity. In addition, the two tests show the significance of capsule pitch on stopping distance and capsule response. Without instrumentation, the boilerplate weighs 4,025 lb (17.90 kN) with a center of gravity 25.7 in. (652.8 mm) from its base. The instrumented boilerplate included twenty-four sensors to record translational accelerations and angular velocities in the vehicle's local coordinate system.

TABLE 1 Swing Test Matrix

1 ft = 0.305 m; 1 fps = 0.305 m/s

Test #	Horiz. Vel. (fps)	Vert. Vel. (fps)	VEL (fps)	Swing Approach Angle (deg)	Capsule Pitch (deg)	Stopping Dist. (ft)
17	20.0	5	20.6	14	-15.0	10.1
18	44.0	5	44.3	6.5	-15.0	60.0
19	58.0	5	58.2	4.9	0.0	96.0
20	58.0	5	58.2	4.9	-15.0	97.2
21	58.0	5	58.2	4.9	-15.0	94.3

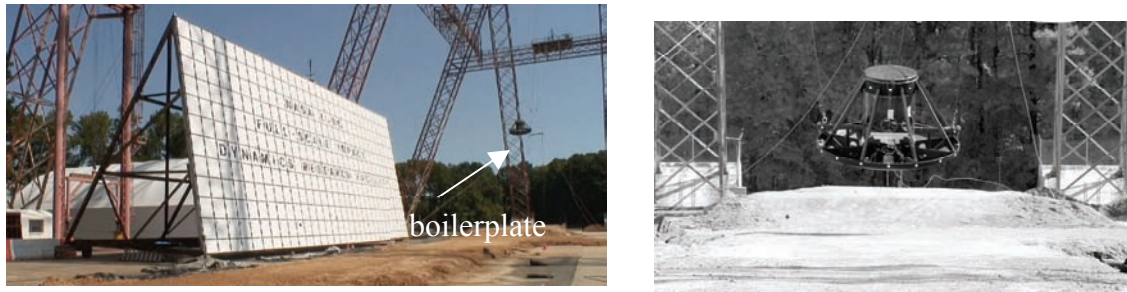


FIGURE 2 LaRC Gantry Crane and Instrumented Boilerplate Capsule Module

SOIL DESCRIPTION

A 42 ft. x 258 ft. (12.80 m x 78.63 m) rectangular soil surface was used as the impact surface for the swing tests. The soil thickness varies between 2 to 3 ft. (0.61 – 0.91 m) and is supported by the LandIR's reinforced concrete test pad.

The soil was analyzed by a soil testing laboratory to determine material properties used for input in the LS-DYNA computer simulations (ARA, 2008). The soil is described as a dense silty-sand material. The soil mat material was originally acquired from a construction fill distributor and used during earlier preliminary Orion/CEV studies. The soil material is only partially protected from rain and is exposed to ambient conditions. Therefore, in-situ material properties vary and are time dependent. Soil preparation for swing tests includes machine compacting and ensuring a smooth top contact surface. The material is classified according to the Unified Soil Classification system as SM, a silty-sand composed primarily of sand with some silty fines. The fines in the soil mixture cause the material to have some plastic behavior. Average values describing the soil include a moist unit density of 130.0 pcf (20.44 kN/m³), 12% moisture content, 3340 psi (23.03 MPa) shear modulus, and 0.193 Poisson's ratio. The high density implies that the soil has undergone heavy compaction. TABLE 2 summarizes the soil material values used in the LS-DYNA analysis (ARA, 2008). In addition to the elastic material properties, coefficients A0, A1, A2, along with a tension pressure cutoff define the material yield surface. The pressure and volumetric strain values represent pressure values as a function of volumetric strain where the volumetric strain is given by the natural log of the relative volume and is negative in compression (see TABLE 2).

TABLE 2 Unwashed Gantry Sand Material Properties for LS-DYNA Input

Mass Density	0.000196 #-sec ² /in ⁴	0.02051 g/mm ³
Shear Modulus	3340 psi	23.03 MPa
Unloading Bulk Modulus	19370 psi	133.56 kPa
Yield Surface Coefficient, A0	6.326 psi	43.62 kPa
Yield Surface Coefficient, A1	3.707 psi	25.56 kPa
Yield Surface Coefficient, A2	0.5432	0.5432
Pressure Cutoff	-1 psi	-6.89 kPa

PRESSURE – VOLUME RELATIONSHIP										
Pressure (psi) + comp	0	10	20	30	40	45	50	55	60	71.15
Pressure (kPa) + comp	0	69	137.9	206.9	275.8	310.3	344.8	379.2	413.7	490.6
Vol. Strain *10 ³ (ΔV/V) + tension	0	-2.52	-4.79	-7.03	-9.17	-10.3	-11.4	-12.5	-13.6	-16

ORION CREW EXPLORATION VEHICLE DESCRIPTION

The Orion is used to transport 6 crewmen, or 4 crewmen and supplies, during a space mission. To enable multiple swing tests to investigate pitch and approach velocity dependency, a boilerplate module was constructed to simulate actual CEV behavior. Capsule retrorockets reduce vertical velocity during landing; therefore, 5 ft/s (1.52 m/sec) was used for vertical velocity. The boilerplate is 8 ft. (2.44 m) wide and 5 ft. - 5.3 in. (1.66 m) high, FIGURE 1. The experimental boilerplate is half-sized geometrically to the actual CEV. A platform within the boilerplate supports lead plates used to develop a target weight, 4,025 lb (17.90 kN), and proper center of gravity location. For the tests discussed in this paper, the center of gravity is located along the model's axes of symmetry at 25.7 in. (652.8 mm) above the model base. The boilerplate capsule was monitored for accelerations and rotation using 24 channels of the digital data acquisition system (DAS). In addition, markers along the boilerplate capsule circumference were monitored continuously during the tests through photogrammetry to record capsule rotation. The instrumented boilerplate model during a swing test is shown in FIGURE 2 where the boilerplate swings at the swing line radius. Pullback lines are used to position

the boilerplate to develop the desired horizontal and vertical velocities at impact. Additional cables are used to position the boilerplate for the set pitch and are released pyrotechnically just before boilerplate-soil initial impact.

PENETROMETER TESTING

Penetrometer test computer simulations were conducted as a precursor to the swing test computer simulations later discussed in this paper. The penetrometer test computer simulations were used to examine numerical modeling accuracy of LS-DYNA's "MAT_SOIL_AND_FOAM" material model. The experimental penetrometer tests were performed in May 2008. However, soil parameters used in the numerical penetrometer soil test model were derived from earlier February 2008 soil field tests (ARA, 2008). An instrumented hemispherical penetrometer was dropped from a 30 in. (762 mm) height during the testing. Four drops were performed over an area of several feet. A self contained DAS and accelerometer recorded data at 0.0003125 second time intervals (3000 samples/s). The test results reveal soil variability.

For the computer simulation, a regular hexahedron, 36 in. (914.4 mm) by 36 in. (914.4 mm) with a 24 in. (609.6 mm) height was used for the soil domain, FIGURE 3. A refined soil mesh is used in the vicinity of the potential contact area between the penetrometer and soil. Along the domain boundary, zero translation and rotation boundary conditions are enforced and used to contain the soil. For a 30 in. (762 mm) penetrometer drop test, the computer simulation begins at 0.85 in. (21.6 mm) above the contact surface at 152.4 in/sec (3871 mm/s) vertical velocity.

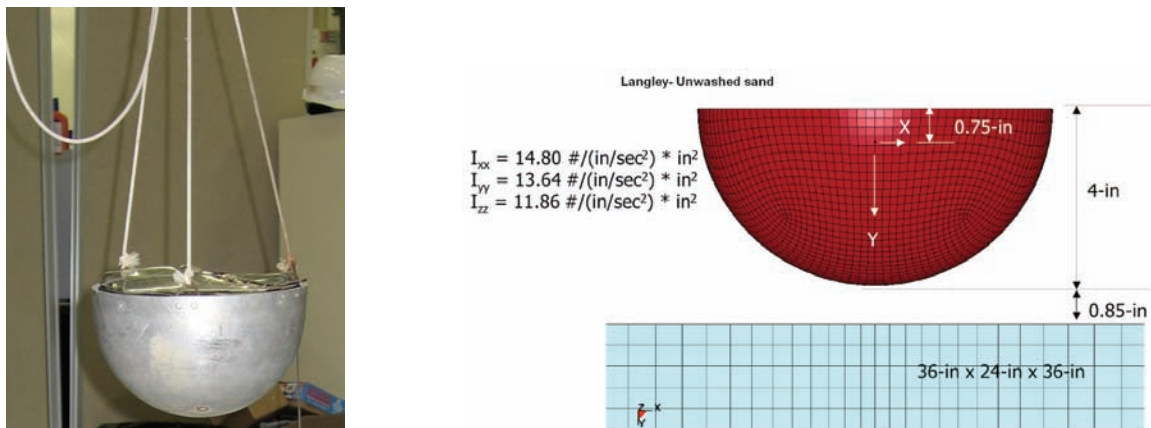


FIGURE 3 Penetrometer Testing

Penetrometer testing results at the four crater locations are shown in FIGURE 4. In addition, LS-DYNA computer simulation results are superimposed on FIGURE 4. Peak acceleration values on FIGURE 4 indicate significant soil strength variability from location to location. Comparing field penetrometer maximum and minimum values for the four holes, soil stiffness varies by 77%. Experimental results show soil stiffness variability as a function of test location. The LS-DYNA computer simulation overestimates all four penetrometer tests. These LS-DYNA inaccuracies imply a too stiff soil domain stemming from inaccurate swing test day soil parameters, domain size, and rigid surface boundary conditions. Actual soil stiffness is time dependent and varies as a function of moisture and compaction. Therefore, if soil sampling is done at a time other than impact test day, LS-DYNA soil test parameters need to be correlated to impact test day conditions. As a result of these inaccuracies, the authors will investigate developing correlation relationships between LS-DYNA parameters and impact test day conditions.

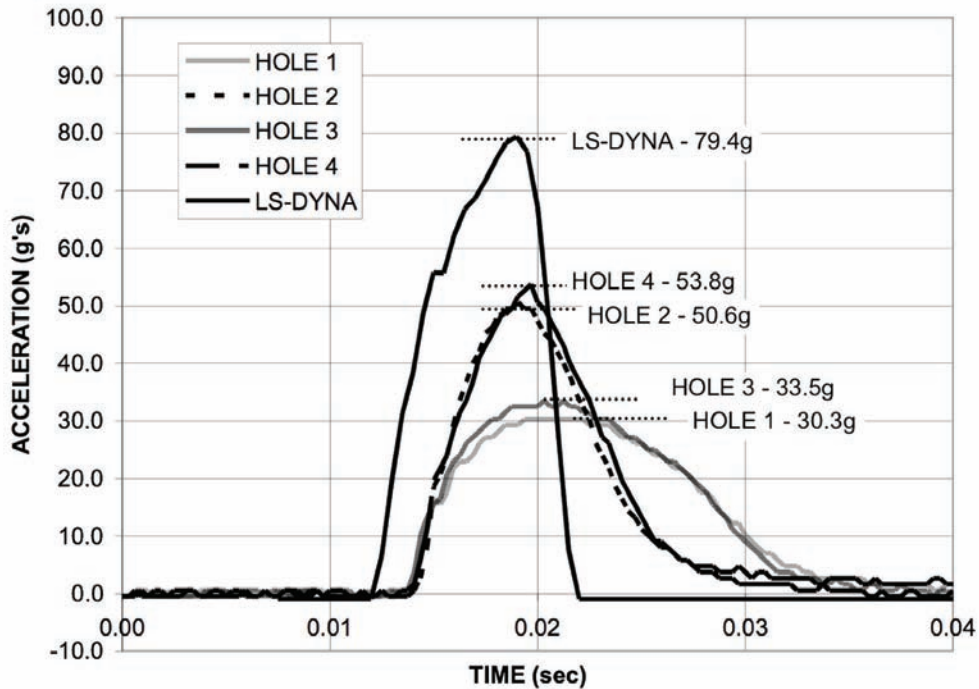
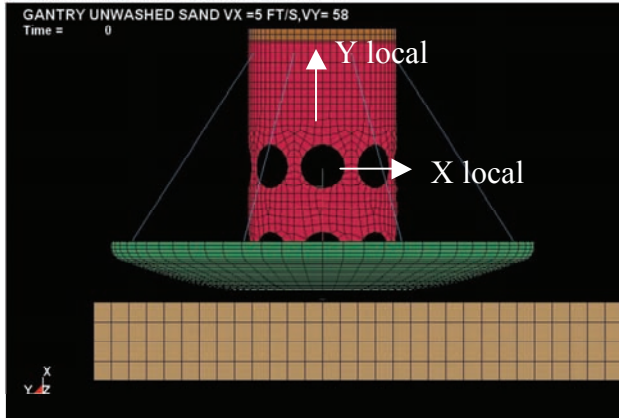


FIGURE 4 Penetrometer Testing Comparing Experimental and Numerical Results

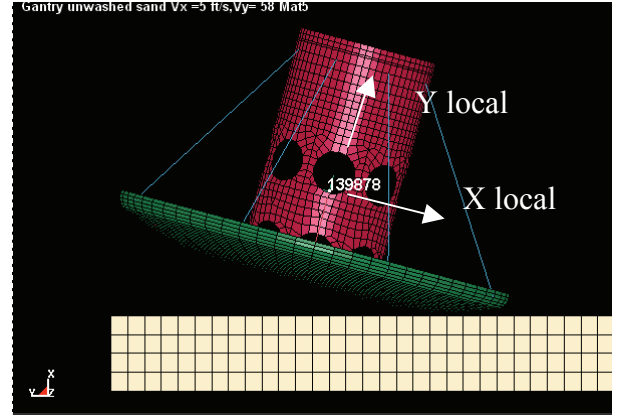
SWING TEST NUMERICAL MODELING

The LS-DYNA finite element analysis computer code was used to numerically model the swing tests performed at LandIR (Hallquist, 2006). FIGURE 5 shows the finite element mesh near initial contact between capsule and soil is shown for two cases, 0° pitch and -15° pitch. FIGURE 5 shows the boilerplate at its initial computer simulation position traveling in the -y global direction (left to right). Initial separation between the boilerplate base and soil is enforced to ensure zero contact at initial horizontal and vertical velocity conditions, 58 ft/sec (17.68 m/s) and 5 ft/sec (1.52 m/s), respectively. The boilerplate is modeled as a rigid body with $I_{y'y'} = 8160 \text{ lb-in-sec}^2$, $I_{x'x'} = 10000 \text{ lb-in-sec}^2$, and $I_{zz} = 10160 \text{ lb-in-sec}^2$, about the vehicle local coordinate system. The soil domain is numerically modeled as a homogeneous material 200 ft. (60.96 m) long, 20 ft. wide (6.10 m), and 1.5 ft. (0.46 m) thick. The 18 in. (457.2 mm) thick soil domain is discretized using constant 4.5 in. (114.3 mm) x 4 in. (101.6 mm) x 4 in. (101.6 mm) soil brick elements, FIGURE 5. Zero translation and zero rotation boundary conditions are enforced along the soil sides and base. Soil material behavior is characterized using LS-DYNA's "MAT_SOIL_AND_FOAM" material model (Hallquist, 2006). The "MAT_SOIL_AND_FOAM" model is fairly straightforward and is used to model soil and crushable foam. However, "MAT_SOIL_AND_FOAM" models soft soil with fluid-like behavior. Consequently, the soil domain needs to be contained through boundary conditions along the soil domain surface to prevent flow due to gravity. In the "MAT_SOIL_AND_FOAM" model, soil behavior is characterized using pressure as a function of volumetric strain. The soil material deviatoric behavior is governed through a pressure dependent rule using three constants, A_0 , A_1 , and A_2 . Soil model constants along with material properties used for "MAT_SOIL_AND_FOAM" are attained through soil laboratory testing.



a) 0° Pitch

FIGURE 5 Model Meshing



b) -15° Pitch

SWING TEST RESULTS

Two swing tests are presented in this paper, one with the capsule at 0° pitch and the other at -15° pitch. Swing Test 19 was conducted with the boilerplate configured at 0° pitch with 58 ft/sec (17.68 m/sec) and 5 ft/sec (1.52 m/s) initial horizontal and vertical velocities, respectively. Swing Test 20 was performed at the same initial impact velocities, however at -15° pitch. The boilerplate skidded 96 ft (29.26 m) and 97 ft (29.56 m) for 0° pitch and -15° pitch, respectively, from its initial contact point. One objective in developing computer simulations for the swing tests was to determine the friction coefficient at the soil–boilerplate interface. Stopping distances derived from LS-DYNA computer simulations are compared with swing test stopping distances in FIGURE 6. From FIGURE 6, the stopping distance versus friction behavior can be approximated within the considered friction as a second-order polynomial. Based on stopping distance, an approximate average friction between the boilerplate and soil is 0.45. In comparison, a block sliding with initial velocity of 58 ft/sec (17.68 m/s) on a solid smooth surface with a 0.45 friction coefficient stops at 116 ft (35.4 m). The difference in the two stopping distances implies the significance of plowing while the boilerplate traverses the soil.

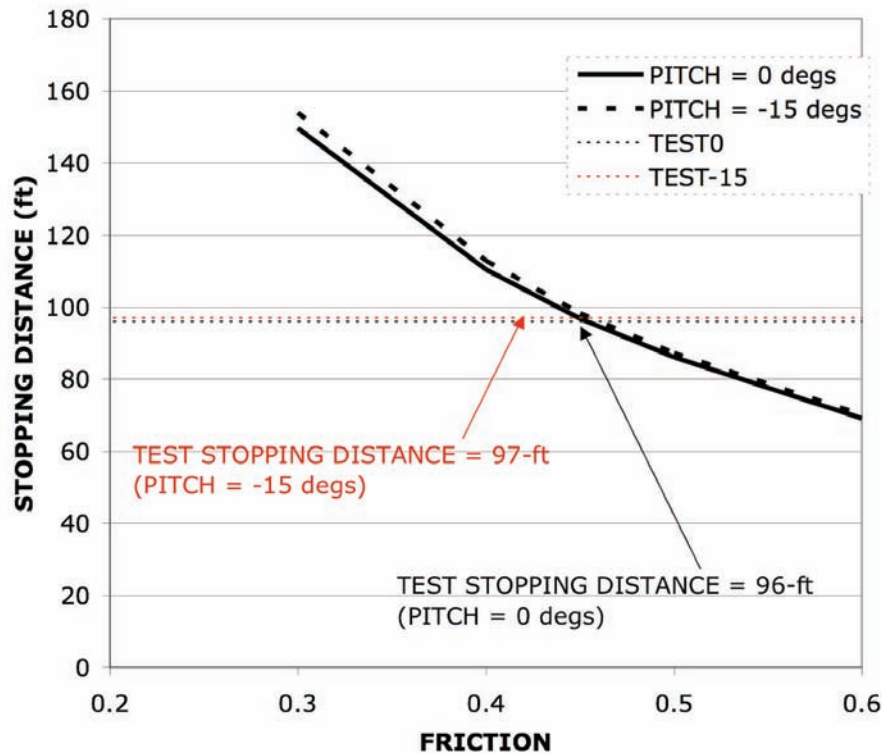


FIGURE 6 Stopping Distance as a Function of Soil-Capsule Friction

LS-DYNA predicted accelerations at the boilerplate center of gravity are compared with Swing Test 19 and 20 experimental accelerations in FIGURES 7 and 8, respectively. Therefore, the figures show model accuracy and pitch significance. Only the first 2 seconds of the time histories are shown for clarity. Accelerations are shown in the vehicle local coordinate system to evaluate payload response. From comparing stopping distance as a function of friction coefficient, a 0.45 friction coefficient was used for the computer simulations. To remove white noise, time histories from the boilerplate instrumentation were filtered using a forward and backward 124 Hz cutoff frequency low-pass digital filter.

Experimental horizontal and vertical acceleration peaks occur concurrently at contact times between the boilerplate and soil. The interaction between the boilerplate and soil causes boilerplate uplift, positive acceleration, and drag, deceleration, in the horizontal direction. At peak positive vertical displacement, the boilerplate returns to earth at $-1g$ in free-fall. Conversely, while airborne the boilerplate experiences 0 horizontal deceleration. The experimental data shows random behavior, indicative of test mat anomalies.

The computer simulations assume constant friction and a level soil impact surface. For 0 pitch, the computer simulations show decreasing energy for capsule impacts after initial impact. Swing Test 20 at -15° pitch also shows similar behavior, but also shows the significance of pitch. Due to rocking, peak accelerations do not uniformly decrease.

Peak acceleration values are shown on FIGURES 7 and 8. The figures show that the computer simulations are able to predict peak vertical acceleration at initial contact fairly reliably. Conversely, horizontal accelerations are more sensitive to boilerplate initial conditions and soil geometry; therefore, horizontal acceleration correlation is not as good. A larger than expected experimental acceleration peak occurs in both the 0° and -15° pitch cases, which is probably due to an anomaly in the soil profile. In the -15° pitch case, experimental results show that the boilerplate experiences significant rocking. The numerical results capture this rocking behavior. At -15° pitch, due to rocking the numerical results show an acceleration increase at the 4th peak. Increasing pitch magnitude increases x_{local} acceleration and reduces y_{local} acceleration. In addition, acceleration frequency increases as pitch magnitude increases. In both pitch cases, the computer simulations capture the general acceleration behavior and contact spacing as a function of time. Discrepancies between results stem from: modeling soil behavior with parameters that do not mimic in situ test day conditions and secondly, using a rigid body model for the boilerplate.

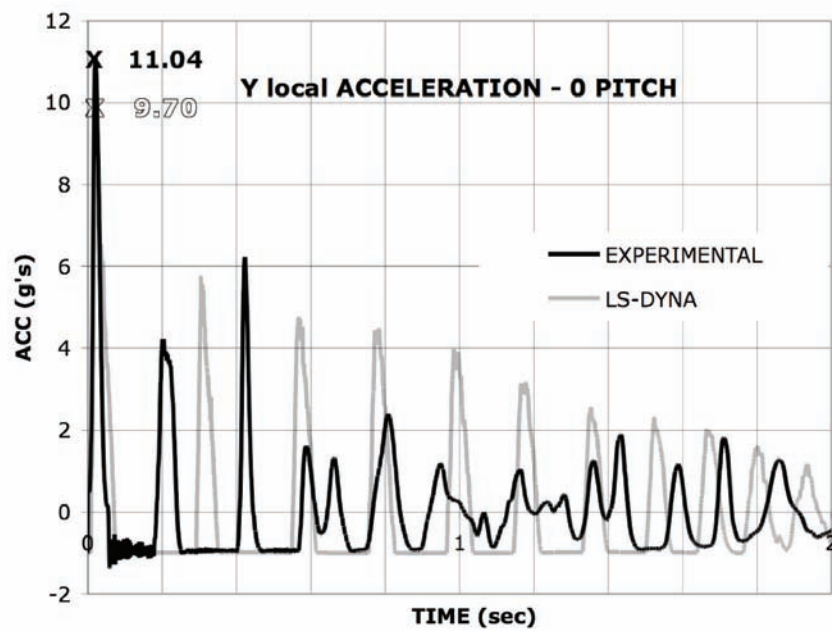
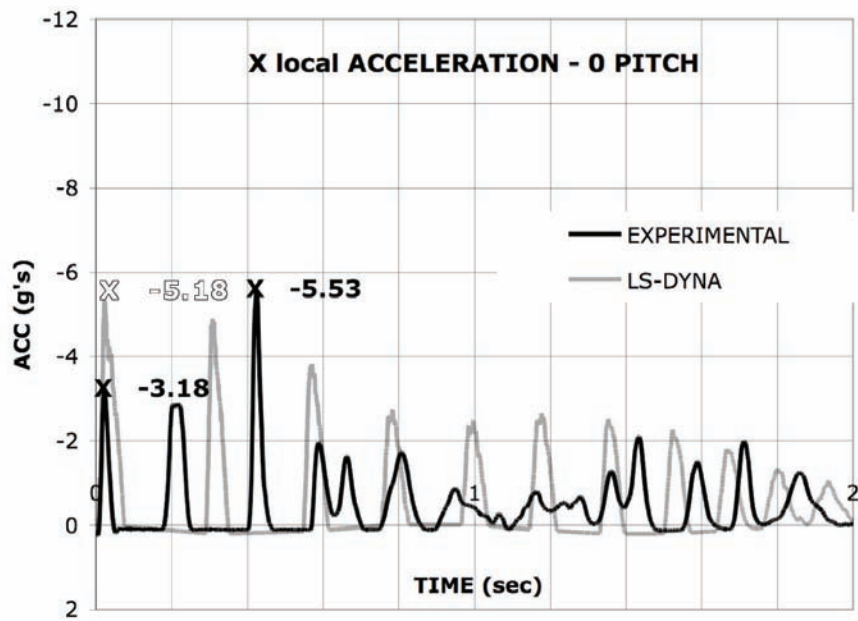


FIGURE 7 Swing Test Acceleration @ 0° Capsule Pitch

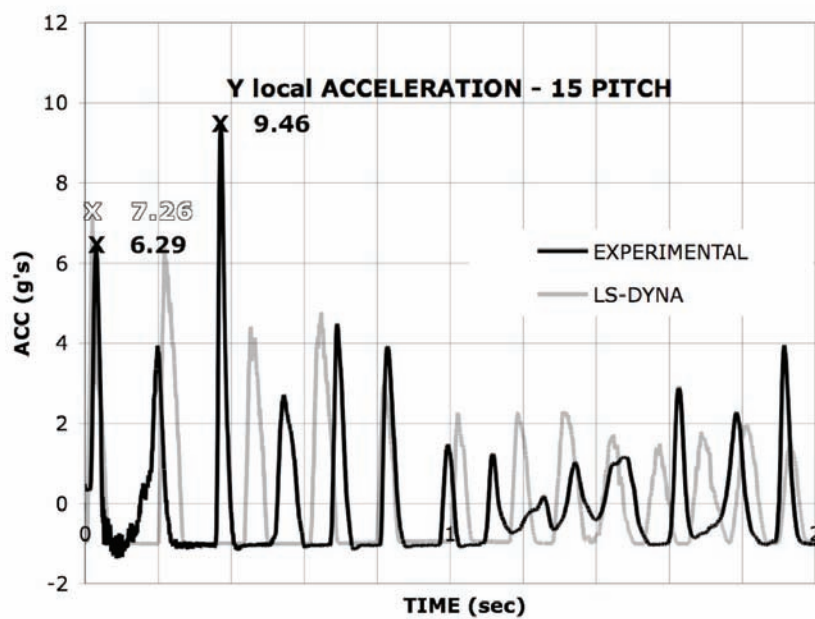
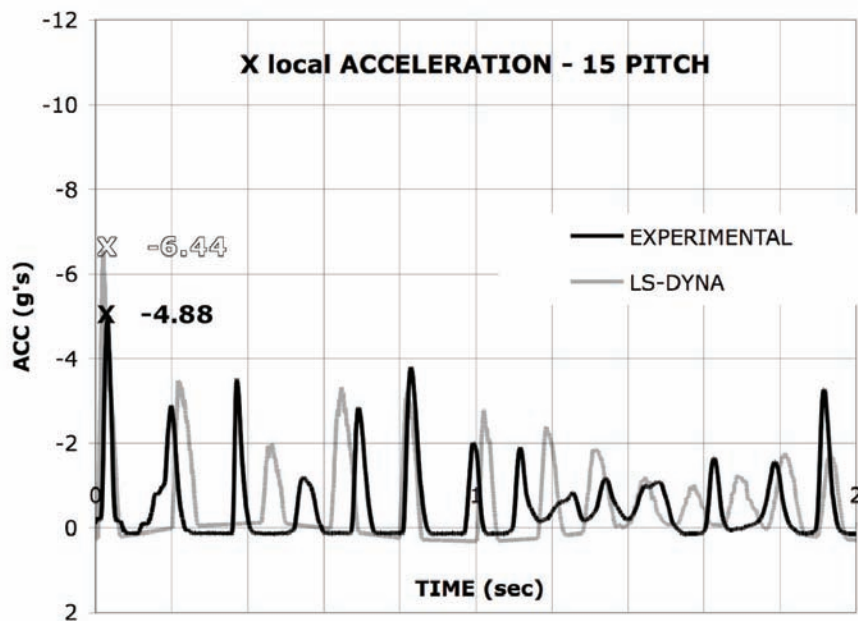


FIGURE 8 Swing Test Acceleration @ -15° Pitch

Computer simulation results for vertical displacement are shown in FIGURE 9 for 0° pitch using a 0.45 friction coefficient. In addition, points locating actual boilerplate-soil interaction from Swing Test 19, 0° pitch, are superimposed on FIGURE 9. The contact

points from the swing test are approximate since the impact points taken from photographs are indecisive. The global coordinate system origin is taken at the boilerplate base at time zero; therefore, the soil surface plane is at -0.5 in. (-645.2 mm). Consequently, soil penetration by the boilerplate occurs when the boilerplate has a negative displacement greater in magnitude than -0.5 in. (-645.2 mm). For the considered friction range, friction causes the boilerplate to skip along the soil surface and have a long stopping distance. For the considered high-density packed soil in this test series, boilerplate penetration into the soil is nominally independent of the friction value. However, the combined effect of soil penetration and soil resistance due to friction causes greater liftoff as contact friction increases.

Although trends can be observed as a function of soil-boilerplate interface friction, FIGURES 7-10 illustrate the actual complex boilerplate behavior due to the combined effects of pitch axis rotation, soil contact, plowing, and friction.

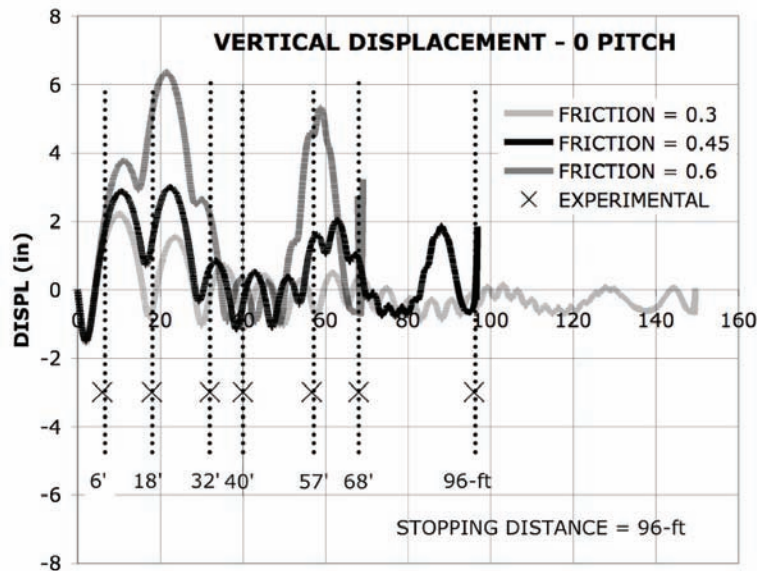


FIGURE 11 Vertical Displacement as a Function of Distance Considering 0° Pitch Angle

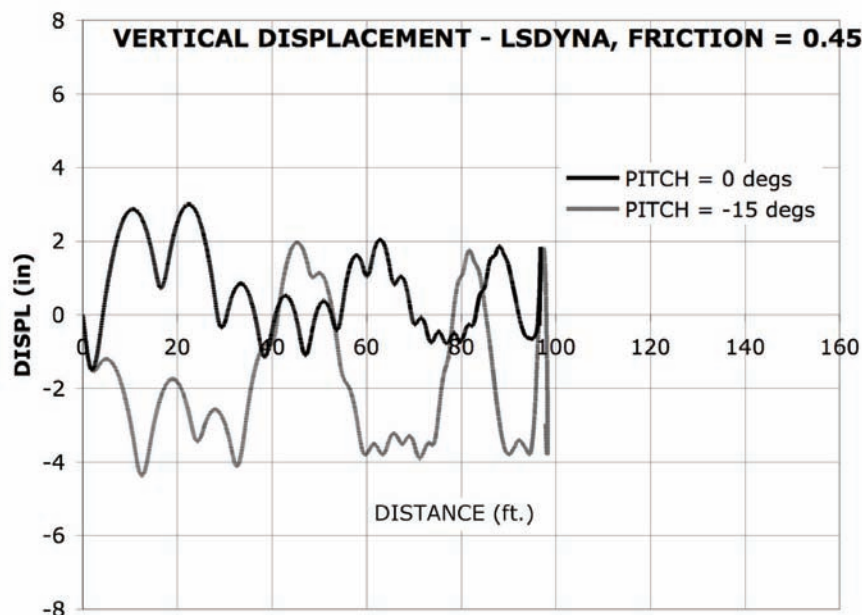


FIGURE 12 Vertical Displacement as a Function of Pitch Angle

CONCLUSIONS

NASA is examining the feasibility of using ground landing for its proposed Orion crew exploration vehicle. The Orion will be used to transport astronauts during space travel and is part of NASA's Constellation Program. Ground landing feasibility is being studied using both experimental swing tests and computer simulations. Experimental swing tests are limited due to expense and time. Conversely, computer simulations provide a means to greatly expand test studies. Consequently, once validated with experimental data, computer simulations will greatly enhance the Orion capsule ground landing investigation.

Twenty-one boiler-plate capsule swing tests were conducted at the NASA Langley Research Center (LaRC) over a 4 month period using the gantry at the LandIR facility. A scaled capsule boilerplate was used to represent a capsule shaped like Orion. Computer simulations of two swing tests, Swing Test 19 (0° pitch) and 20 (-15° pitch), are presented in this article and compared with the experimental swing test results. The computer simulations were developed using LS-DYNA, an explicit nonlinear dynamic finite element code. Results show the complex boilerplate behavior that exists during swing testing. Modeling the soil as a homogeneous, perfectly flat material leads to

inaccuracies. Further inaccuracies stem from using soil material values in the computer simulations from soil testing conducted at a time other than the swing test day. Even with these soil inaccuracies, computer simulations replicated the maximum vertical initial peak accelerations and captured the general boilerplate behavior. In future work, the authors will investigate methods to calibrate soil parameters initially developed for the LS-DYNA soil input with swing test day in situ soil conditions.

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